AIAA-2000-5062

IN-SITU EXPLORATION OF MARS USING ROVER SYSTEMS

Eric T. Baumgartner
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

ABSTRACT

This paper will describe a NASA/JPL rover system that has been focused on developing technologies required for the in-situ exploration of Mars. In particular, JPL has been developing a class of rovers that carry significant science payloads that address geological exploration and discovery along with the ability to acquire samples from soils and rocks. The aim of this work is to validate mission concepts and to gain valuable experience related to the operation of rovers on Mars so that improved mission operations and scientific return can be realized during future flight missions.

INTRODUCTION

For the scientific exploration of a planetary surface using a rover system, many technical challenges must be addressed in the design and development of the planetary rover. This paper outlines some important issues that are critical to rover systems. This paper will also detail the JPL Field Integrated Design and Operations (FIDO) Rover and the use of this robotic system within terrestrial field trials to validate and support rover operations associated with sample identification, in-situ analysis of rock samples, sample acquisition, and sample return to a landed element. FIDO conducted a set of field trials in 1999 and 2000 that validated the required mission operations associated with the Athena rover mission as envisioned for the Mars Program Surveyor mission set[1]. The FIDO rover is shown in Figure 1 during operations associated with the May 2000 field trial near Lunar Lake in Nevada.

The development of FIDO over the past two years utilized significant technology developments from the core NASA robotics technology program. This includes software components from the Rocky7 rover[2] and the Sample Return Rover[3] as well as hardware components in the areas of advanced planetary manipulators[4], advanced in-situ instruments[5], and drilling systems for sample acquisition. These systems and components have been integrated and further developed by the FIDO rover team resulting in a complete science rover. The team also worked closely with a group of Mars scientists who assist with the definition of requirements for the FIDO instrument suite along with the definition of the rover's mission operation concepts.

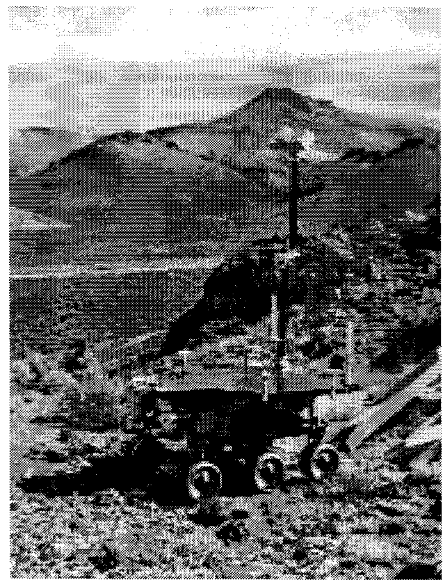

Figure 1: FIDO at the Lunar Lake field site.

The following section provides insight into some of the critical technology areas associated with in-situ robotic exploration. The paper will then describe the technical details associated with the FIDO rover. Some representative results from the April 1999 and May 2000 field trial will also be presented. The paper concludes with some summary remarks regarding in-situ exploration using rovers.

CRITICAL TECHNOLOGY AREAS

Planetary surface exploration using rovers provides a unique challenge to the development of robust and reliable robotic systems. Because the environment in which the rover is operating is completely unstructured and very remote, the system as a whole must rely on a set of hardware and software that can keep the rover safe throughout its operations. In addition, the rover must provide the scientific community with the means for completing the required goals of the mission. As a result, the development of any planetary rover system must address the following key technical issues:

1. Surface mobility
2. Rover localization
3. Obstacle detection and avoidance
4. Instrument placement and control
5. In-situ sample acquisition
6. Autonomous operation including fault detection and recovery

The first issue is associated with the rover's ability to safely traverse within a particular terrain environment that is typically described in terms of rock distribution, rock heights, and terrain slope. Surface mobility is therefore a function of the mobility type (rolling, walking, crawling, etc) and the physical properties of the mobility system (wheel diameter, ground pressure, leg length, etc). While many researchers have looked at various types of mobility systems, JPL's main focus is the development of wheeled rover systems. Wheeled systems are easy to operate and have low mass, power and volume constraints when compared to alternative mobility approaches. For the mobility configuration of a wheeled system, Wilcox et al[6] analyzed mobility dimensions given a particular rock distribution to determine optimal rover configuration.

The second technology issue, rover localization, is defined as knowing the position and attitude of a rover with respect to a particular reference frame (either global or local). Rover localization is typically addressed by fusing together a number of sensor sources such as wheel odometry, rate sensors, acceleration sensors, heading sensors, and range sensors. State estimation techniques address this particular issue by providing the means for fusing together various sensor sources such that an optimal estimate of the rover's position and attitude is determined[7]. For the planetary exploration problem, rover localization is important for accurate rover traverses to a particular science target located within the local vicinity of the rover (e.g. 10-50 meters). Maintaining accurate rover localization over long traverses is difficult due to the lack of any global positioning system as is available on the Earth. For long-range rover localization on a planet surface, known horizon features must be utilized to assist with state estimation problem.

The next issue is obstacle detection and avoidance which is the ability of a rover to safely navigate throughout a terrain that is filled with obstacles such as rocks, craters, slopes, etc. The Sojourner rover[8], which successfully operated on the Martian surface in 1997, utilized a laser ranging technique for generating a 3D map of the terrain in front of the rover. However, the density of the range map was quite sparse. Most planetary rovers in operation today utilize stereo imaging systems to generate a dense range map of the terrain surrounding the rover. The computational requirements for generating stereo range maps are typically high, however, the power required is small when compared to laser range finders. To date, many researchers have developed obstacle detection and avoidance algorithms for natural terrain navigation.

The fourth issue, instrument placement and control, refers to the ability to place a scientific instrument precisely on or against a target of interest. On the Sojourner rover, the Alpha Proton X-Ray Spectrometer (APXS) was deployed using a single degree-of-freedom 4-bar linkage with passive compliance that allowed the instrument face to conform to the rock or soil surface on which it was placed. Other approaches utilize higher degree-of-freedom mechanisms, such as robot arms, to position and orient a science instrument with respect to the target. Some planetary rovers utilize four and five degree-of-freedom manipulators for instrument placement.

In addition to the physical mechanism used for instrument placement, the means for planning the appropriate motion of the manipulator so that there is a successful deployment of the instrument is an important issue as well. In particular, various sensors are used to aid in the planning and operation of an instrument-laden robot arm. The most common approach for instrument deployment consists of utilizing a 3D map of the terrain generated by a stereo camera pair to identify the 3D position of a science target and the surface normal associated with that target. This 3D location and surface normal are then represented relative to the base frame of the arm using the known geometric relationship between the stereo camera pair and the arm. Finally, using the inverse kinematics of the arm, the joint rotations that move the arm along a collision-free path to the terminal location is determined. Typically, inaccuracies in the 3D range maps and the kinematics of the arm will result in the imprecise placement of the instrument. Touch sensors or force sensors are, therefore, used to sense contact with the surface. In addition, advanced manipulation techniques utilize vision to control the robot arm throughout its motion until termination at the target. Two well-studied techniques are known as visual servoing[9] and camera-space manipulation[10,11].

The next technology issue is concerned with the ability to robustly and reliably obtain rock and/or soil samples from a planet surface. The development of in-situ sample acquisition devices typically focuses on either soil scooping mechanisms mounted on robot arms or drilling systems that allow for a core to be extracted from a rock. For example, one of the payload elements for the recently-lost Mars Polar Lander mission included a robot arm known as the MVACS arm that was used to dig into the Martian surface, scoop the soil, and deposit this soil in a science instrument located on the deck of the lander[12]. As part of the Athena rover mission, a miniature core drill will be used to collect rock and soil samples[1]. A strong priority within the science community is the concept of sample return from the Martian surface to help in determine if there was ever life on Mars. Shallow rock drilling from a mobile platform will certainly play an important role in sample acquisition. Critical issues associated with drilling from a mobile platform include autonomous operation without drill fouling, rover positioning over the required drill target, and planetary protection issues such as forward and backward contamination.

The final issue that is noted in this section is associated with autonomous rover operation including fault detection and recovery. Current mission scenarios call for a 90-day operation on the surface of Mars with telecommunication passes in the Martian morning and evening. With only two opportunities to receive commands from Earth and to downlink telemetry to Earth, the rover will spend the majority of the time operating on its own with minimal interaction with ground controllers. Unlike most terrestrial robotic applications, in-situ rovers must be capable of operating completely autonomously. This includes carrying out the requested science and mobility commands received from ground controller as well as health monitoring, fault detection, and fault recovery. Currently if faults occur during the performance of a command sequence, the rover will evoke a pre-determined fallback sequence and wait for further instructions from ground controllers. Researchers are currently working on conditional sequencing and planning for on-board rover software that will be capable of branching to various sequences in response to particular faults.

THE FIDO ROVER

The FIDO rover to some degree addresses each of the critical technology areas described in the previous section. As such, FIDO represents a central integration platform for the development and testing of advanced robotic technologies. This rover has been utilized over the past two years by the Mars science community to test and validate mission concepts associated with robotic surface exploration and discovery as well as sample collection. FIDO successfully completed two field trials in April 1999 at the Silver Lake Field Ste near Baker, California, and in May 2000 at the Lunar Lake Volcanic Field Ste in Central Nevada.

FIDO's mobility sub-system consists of a 6-wheel rocker-bogie suspension system that was scaled up by a factor of 20/13 from the Sojourner rover's design. This suspension system allows for the safe traverse over obstacles up to 30 centimeters in height. Each wheel is independently driven and steered using a Sojourner-derived actuation and encoder system. The top ground speed of the vehicle is 9 centimeters/second. Approximate rover dimensions are 1 meter in length, 0.8 meters in width, and 0.5 meters in height with a 0.23 meter ground clearance height. The rover carries a four degree-of-freedom deployable mast that stands 1.94 meters off of the ground surface at full extent. This mast provides the necessary pan and tilt control for panoramic imaging and point spectroscopy. FIDO also carries four degree-of-freedom instrument arm that is utilized to place the in-situ instrument suite on rock and soil targets.

FIDO's remote sensing suite located on the mast includes a multi-spectral, narrow field-of-view PanCam stereo imaging system, a monochromatic, wider field-of-view NavCam stereo imaging system, and the optics for a near-infrared point spectrometer that operates in the 1200 – 2500 nanometer wavelength region. The multi-spectral capability associated with the PanCam system is realized using a Liquid Crystal Tunable Filter (LCTF) that is tuned to the three near-IR wavelengths of 650, 750 and 850 nanometers. The in-situ instrument suite that is attached to the end-effector of the FIDO instrument arm consists of a color microimager and a Moessbauer spectrometer that is used to determine the iron content of target rocks. Finally, a miniature core drill system is body-mounted to the rover and provides the capability to acquire and cache rock and soil samples. In addition to the two pairs of stereo cameras mounted on the top of the FIDO mast (PanCam and NavCam) that are used for long-range navigation, FIDO includes two other stereo pairs located on the front and the back of the rover body at 50 cm above the ground. These cameras (called HazCams) have a wide field of

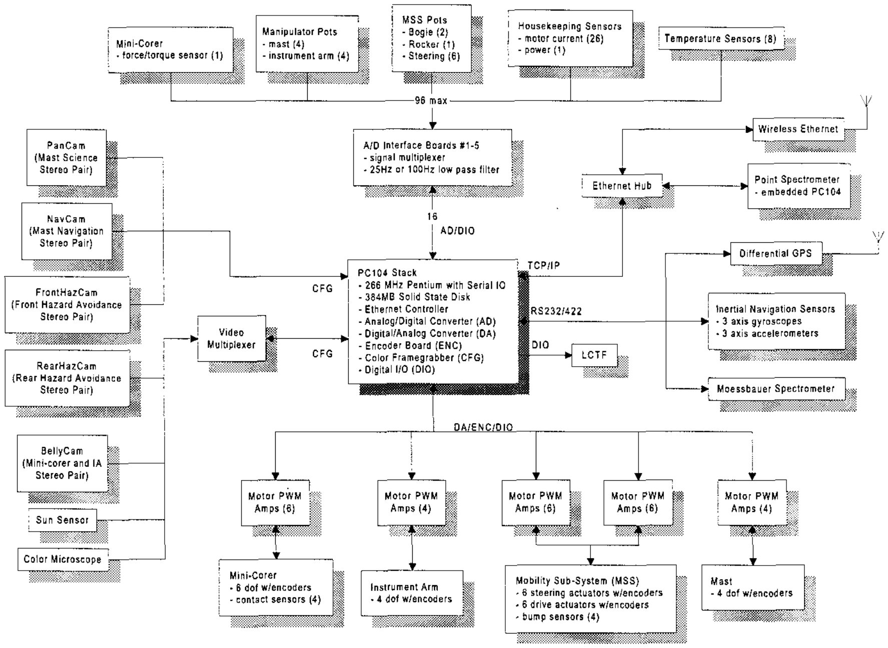

Figure 2: Functional block diagram for the FIDO rover.

view and are used for local obstacle avoidance. Finally, a stereo pair called the BellyCam is mounted on the underside of the rover and is used to view the operation of the mini-corer.

The electronics for the FIDO rover are built around the commercially available PC104+ embedded computer architecture. FIDO carries a CPU board with a 266 MHz Intel Pentium processor, separate PCI and ISA data buses, 4 RS232/422 serial I/O ports, 2 USB ports, and 1 parallel port. Current CPU memory is 64 Mbytes. Included on the PCI bus is a 100 Mbps full duplex ethernet board and two 4-channel color framegrabber boards. Included on the ISA bus are the following: one 96 channel digital I/O board; one 16 channel, differential input, 12 bit resolution analog-to-digital conversion board; one 32 channel, 8 bit resolution digital-to-analog conversion board, and two 15 channel, 16 bit resolution encoder interface boards. The FIDO electronics also include five 16 channel, differential input, 25Hz or 100Hz low-pass filter boards that serve as an analog multiplexer and signal conditioning board. The functional block diagram of the FIDO electronics is shown in Figure 2.

Closed-loop motion control of all 26 actuators on-board FIDO is carried out in software utilizing either encoder or potentiometer feedback from each motor and a PWM amplifier based on National Semiconductor's LMD18245 fill-bridge motor driver chip. A set of 6 PWM amplifiers are included on a single motor driver board and FIDO carries a total of 5 motor driver boards. Control of all actuators occurs at 50Hz and closed-loop PID velocity, PID position, and PID fuzzy velocity controllers have been implemented within the FIDO software environment.

The operating system (OS) utilized on the rover is the real-time VxWorks 5.3 operating system. The OS is resident on a 384 Mbyte solid state flash disk and is turnkey bootable upon startup of the rover system. All rover software is written in ANSI C and is organized into a three-layer software architecture. The lowest layer, known as the *device driver* layer, is responsible for direct interactions with the electronics hardware. The middle layer, called the *device layer*, is responsible for all motion control, vision processing, instrument interfaces, rover forward and inverse kinematics, etc. and provides the means for abstracting higher-level software from hardware dependencies. The highest-level, known as the *application layer*, contains all rover sequences, instrument sequences, waypoint navigation algorithms including hazard detection and avoidance, etc. Figure 3 shows a diagram indicating the functional organization of the FIDO software architecture.

The mission operations tool for the FIDO rover, known as WITS (Web Interface for TeleScience)[13], is a distributed operations tool that allows scientists and engineers to view rover telemetry and build rover

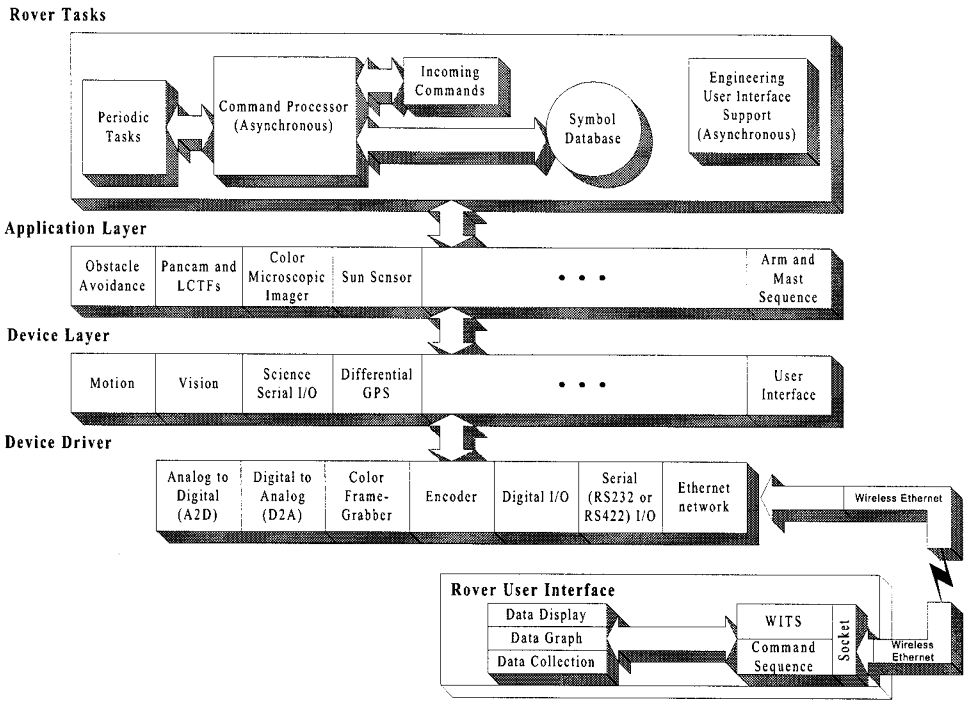

Figure 3: FIDO software architecture block diagram.

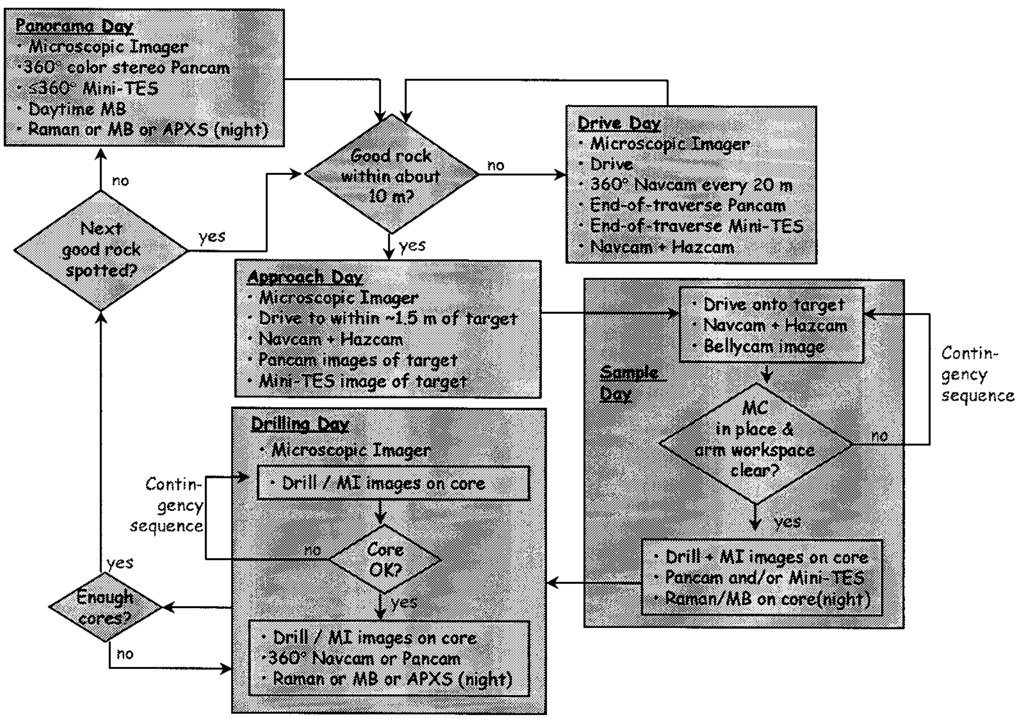

Figure 4: Athena rover mission operations flow.

sequences over the Internet. WITS was the primary operations tool for the Mars Polar Lander (MPL) flight mission and was used for the operation of the robot arm and stereo imager. The version of WITS utilized during the MPL flight mission was developed in parallel with the version of WITS that was used for FIDO. In addition to sequence building, WITS offers the ability to simulate a sequence to validate the sequence flow as well as the physical positioning of the rover with respect to a virtual 3D terrain environment.

FIDO FIELD TEST ACTIVITIES

As stated in the previous section, FIDO conducted two major field tests in April 1999 at the Silver Lake site north of Baker, California and in May 2000 near the Lunar Lake site in central Nevada. Both of these tests aimed to validate the mission concepts associated with the Athena rover mission. A representative mission flow diagram that describes the operation of the Athena rover on the Martian surface is shown in Figure 4.

During the Silver Lake test, the entire science and engineering team was located out in the field with the rover. The team was able to view first-hand the operation of the rover within its environment. During the Lunar Lake test, a small engineering team accompanied the rover to the field. The primary science and engineering team was sequestered in a mission operations room at JPL. In this way, the science and engineering team was "blind" to the field site and only discovered information about the field site through the "eyes" of the rover in addition to orbital and simulated descent images. The goal of the Lunar Lake test was to run the mission as if the rover was on Mars. In addition to these two field tests, FIDO has undergone many operational readiness tests in JPL's MarsYard which is an outdoor facility that includes many rocks of varying size and distribution.

The Silver Lake test represented FIDO's first major field trial and the majority of the rover operations consisting of simulating sample collection using the miniature core drill located on FIDO. Figure 5 shows FIDO operating at the Silver Lake site with both the mast and instrument arms deployed. These tests are summarized by Arvidson et al[15] and highlights include the successful acquisition of two rock samples by the mini-corer. Figure 6 shows the FIDO mini-corer drilling into a dolostone rock along with a view of the hole produced by the drill as seen by the rover's BellyCam. Confirmation of the core extracted by the drill was accomplished using the color microimager which in its stowed position is able to look up into the drill stem of the mini-corer. Other elements of the Silver Lake field trial included a long-distance

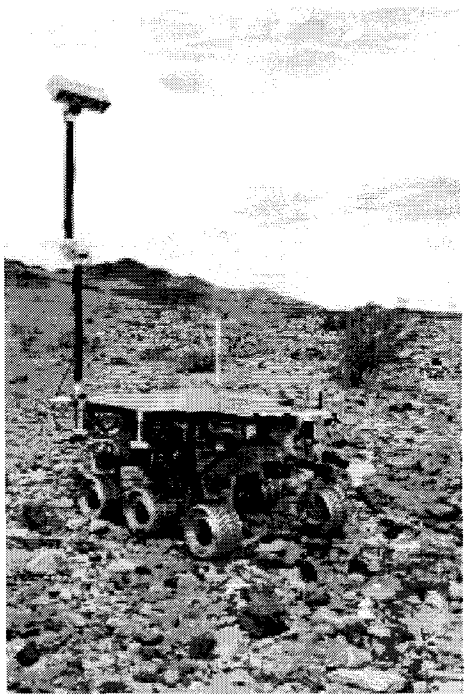

Figure 5: FIDO operating at the Silver Lake field site.

traverses, exploration along a water-formed breakout channel, and an educational outreach program that allowed students from around the country to command FIDO via the WITS operations environment[16].

The Lunar Lake field trial focused on exploration and discovery in an attempt to understand the geological history of the environment. The science team at JPL used FIDO's in-situ instrument suite along with spectral data and visual images taken from orbital and aerial platforms including simulated descent images to understand the geology of the site. During this test, the science team primarily used the mast-mounted PanCam and infrared point spectrometer along with the color microimager mounted on FIDO's instrument arm to correlate geological hypotheses generated from the orbital and aerial data. The tests showed that remote geology is indeed possible using an in-situ robotic vehicle with the science team successfully identifying the geology of the site to within an 80% accuracy[17,18]. Some representative data products from the Lunar Lake field test are shown in Figures 7, 8, 9 and 10. Figure 7 shows a panorama taken from FIDO's NavCam while the rover was located on top of the deck of a simulated lander. The lander also includes a set of ramps that were used for the FIDO's egress off of the lander deck. An image from the PanCam is shown in Figure 8. Here the image is shown in black and white, however, three

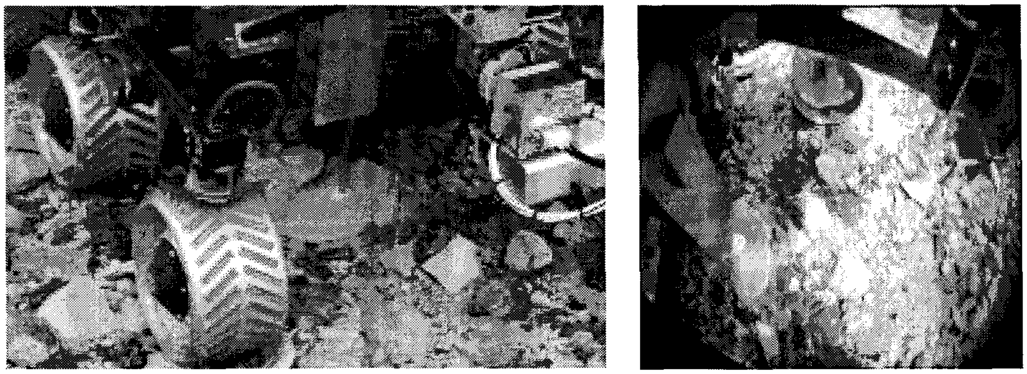

Figure 6: Mini-corer operation (left) and BellyCam image of drill hole (right).

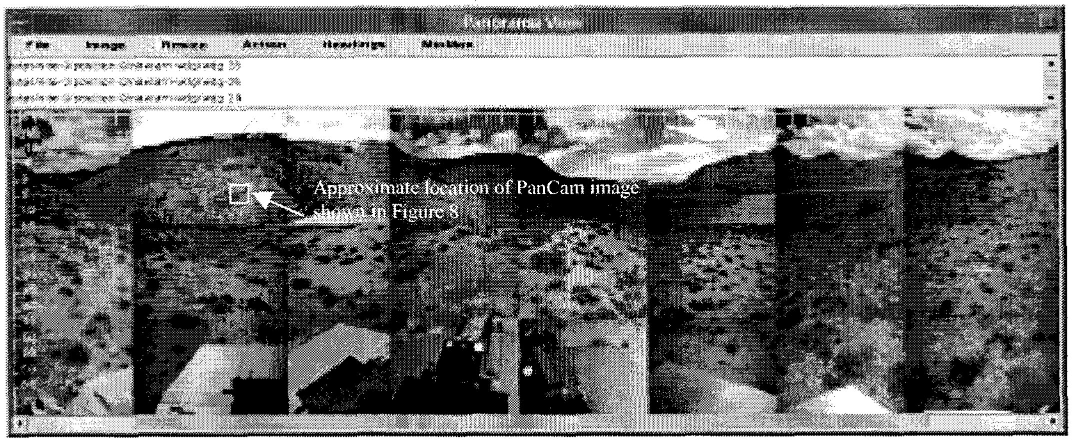

Figure 7: NavCam panorama from top of lander deck.

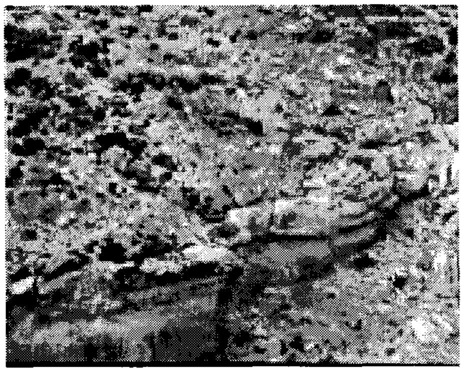

Figure 8: PanCam image of wall face (three-color composite shown in black and white).

colors in the near infrared make up the composite PanCam image as described in the previous section. Figure 9 shows a representative spectrum collected by the near-infrared point spectrometer which identifies the mineral dolomite in the target sample indicating the previous presence of water at the field site. Finally, Figure 10 shows an image taken from the color microimager of rocks located on the ground at the field site. The image size is 15 mm by 15 mm where the material on the leftmost rock in the image (red, yellow, and white material in the color image) indicates the presence of living and dead lichens on the rock surface.

The Lunar Lake field trial also included a three-day joint rover operation with the K9 rover that has recently been developed at NASA Ames Research Center. The mobility system for the K9 rover is identical to FIDO's, however, the electronics and instruments for K9 were developed at NASA Ames. The K9 rover was utilized as a scout rover in order to find and characterize rocks that were valid for drilling by FIDO. The FIDO rover then served as the sampling rover and was used to approach the rocks characterized by K9 for the purpose of drilling these rocks with the FIDO mini-corer. Finally, the Lunar Lake field trial included a student outreach activity similar to the Silver Lake field trial.

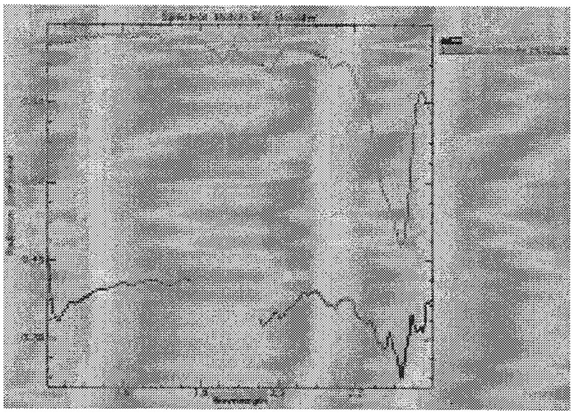

Figure 9: Representative near-infrared point spectrum.

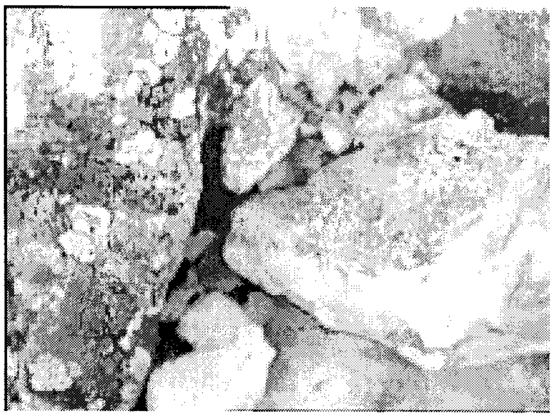

Figure 10: Image from the color microimager (RGB image shown in black and white).

Students from around the country commanded FIDO remotely using WITS in an attempt to bring the rover back to the lander and return any collected samples to the deck of the lander. The tests concluded with the autonomous detection and navigation to the bottom of the lander ramps using a software component provided to FIDO by JPL's Sample Return Rover task. Once the rover reached the bottom of the lander ramps, the vehicle was commanded to drive back up the ramps and stop on top of the lander deck.

CONCLUSIONS

The paper has presented some of the critical issues that face developers of robotic vehicles that are required to conduct in-situ science analysis and sample acquisition. This paper has also presented details concerning the design and operation of the FIDO rover including the manner in which this vehicle has addressed the critical technical issues associated with in-situ robotics. Finally, the paper has documented some of the results gathered during the two major field trials conducted by the FIDO rover and how this vehicle has been successfully utilized to test mission concepts associated with planned robotic Mars surface operations. The experience gained by the team of scientists and engineers associated with FIDO has been vast. It is the hope of the FIDO team that this experience will be passed along to those individuals responsible for the development of a flight rover system so that in-situ rover operations are optimized and scientific return is maximized.

ACKNOWLEDGMENTS

The author would like to acknowledge and thank all of the people associated with the FIDO task for all of their work associated with the rover system. The FIDO team is a large and diverse team of scientists and engineers that have made this vehicle a first-class science rover.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

[1] S. W. Squyres et al, "The Athena Mars Rover Science Payload," 29th Lunar and Planetary Science Conference, Abstract #1101, Lunar and Planetary Institute, Houston, 1998.

[2] R. Volpe, J. Balaram, T. Ohm, R. Ivlev. "Rocky 7: A Next Generation Mars Rover Prototype," *Journal of Advanced Robotics*, 11(4), December 1997.

[3] P. S. Schenker et al, "New Planetary Rovers for Long-range Mars Science and Sample Return," *Proceedings of Intelligent Robots and Computer Vision XVII: Algorithms, Techniques, and Active Vision*, SPIE Vol. 3522, pp. 2-15, October 1998.

[4] H. Das, X. Bao, Y. Bar-Cohen, R. Bonitz, R. Lindemann, M. Maimone, I. Nesnas, C. Voorhees, "Robot manipulator technologies for planetary exploration," Proceedings of the Smart Structures and Integrated Systems Symposium, Newport Beach, CA, March 1999.

[5] FIDO Instruments Web Page located at http://fidoinstruments.jpl.nasa.gov/.

[6] B. Wilcox, A. Nasif, R. Welch, "Implications of Martian Rock Distributions on Rover Scaling,"

Planetary Society International Conference on Mobile Robots and Rover Roundup, Santa Monica, CA, January 1997.

[7] B. D. Hoffman, E. T. Baumgartner, T. L. Huntsberger, P. S. Schenker, "Improved Rover State Estimation in Challenging Terrain," *Autonomous Robots*, Vol. 6, pp. 113-130, 1999.

[8] J. Matijevic, "Sojourner: The Mars Pathfinder Microrover Flight Experiment," Planetary Society International Conference on Mobile Robots and Rover Roundup, Santa Monica, CA, January 1997.

[9] S. Hutchenson, G. D. Hager, and P. I. Corke, "A Tutorial on Visual Servoing Control," *IEEE Transactions on Robotics and Automation*, 12(5), October 1996.

[10] S. B. Skaar and E. Gonzalez-Galvan, "Versatile and Precise Manipulation using Vision," *Teleoperation and Robotics in Space*, pp. 241-279, S. B. Skaar and C. F. Ruoff, editors, AIAA Press, Washington, DC, 1994.

[11] E. T. Baumgartner and P. S. Schenker, "Autonomous Image-Plane Robot Control for Martian Lander Operations," *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 1, pp. 726–731, Minneapolis, MN, April 1996.

[12] Robert G. Bonitz, "Mars Surveyor '98 MVACS Robotic Arm Control System Design Concepts," *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 3, pp. 2465 -2470, Albuquerque, NM, April 1997.

[13] P. G. Backes, K. S. Tso, G. K. Tharp, "The Web Interface for Telescience," *Presence*, Vol. 8, No. 5, pp. 531-539, October 1999.

[14] P. G. Backes, K. S. Tso , J. S. Norris, G. K. Tharp, J. T. Slostad, R. G. Bonitz, and K. S. Ali, "Internet-Based Operations for the Mars Polar Lander Mission," *Proceedings IEEE International Conference on Robotics and Automation*, San Francisco, CA, May 2000.

[15] R. A. Arvidson, S. W. Squyres, E. T. Baumgartner, L. Dorsky, and P. S. Schenker, "Rover Trials for Mars Sample Return Prove Successful," *EOS Transactions*, Vol. 81, No. 7, pp. 65,72, February 2000.

[16] R. E. Arvidson, et al, "Students Participate in Mars Sample Return Rover Field Tests," *EOS Transactions*, Vol 81, No. 11, pp. 113,117, March 2000.

[17] R. E. Arvidson, E. T. Baumgartner, P. S. Schenker, S. W. Squyres, FIDO Field Trials in Preparation for Mars Rover Exploration and Discovery and Sample Return Missions, Lunar and Planetary Workshop on Concepts and Approaches for Mars Exploration, Abstract 6018, July 2000.

[18] B. Jolliff, et al, "Remotely-sensed Geology from Lander-based to Orbital Perspectives: Results of FIDO Rover Field Tests, Lunar and Planetary Workshop on Concepts and Approaches for Mars Exploration, Abstract 6160, July 2000.